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To my past, present, and future family.

"You're braver than you believe, and stronger than you seem, and smarter than you think."

- A.A. Milne, Christopher Robin

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"If you don't know, the thing to do is not to get scared, but to learn."

- Ayn Rand, Atlas Shrugged

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"It's the job that's never started as takes longest to finish."

- J.R.R. Tolkien, The Lord of the Rings

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"I am a wife-made man."

- Danny Kaye

"I knew when I met you an adventure was going to happen."

- A.A. Milne, Winnie the Pooh

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Abstract

This work presents two searches for a high-mass Higgs boson in the $H \to WW \to \ell\nu qq$ decay channel using the ATLAS detector to analyze the high-energy proton-proton collisions provided by the Large Hadron Collider at two different center-of-mass energies, $\sqrt{s} = 8\,\text{TeV}$ in 2012 and $\sqrt{s} = 13\,\text{TeV}$ in 2015, corresponding to two independent datasets with sizes given by their integrated luminosities of 20.3 fb^{-1} and 3.2 fb^{-1}, respectively.

No significant excess of data above the expected background is observed in either analysis, so upper limits are set on the production cross-section times branching ratio, as a function of the hypothesized boson mass, for the various signal models tested. The derived limits substantially improve upon previous results.

Chapter 1

Introduction

> *"There is nothing like looking, if you want to find something. You certainly usually find something, if you look, but it is not always quite the something you were after."*
>
> \- J.R.R. Tolkien, The Hobbit

It has been a driving question throughout the history of science: What are the fundamental constituents of matter and how do they interact with one another? Particle physics addresses this question directly. The contributions of many physicists over the decades, has culminated in an impressively descriptive and predictive theory of the fundamental constituents of matter and their interactions, referred to as the Standard Model.

The recent discovery of the Higgs boson, as predicted by the Standard Model, is a pinnacle moment in the validation of the particle physics theory. However, there are still many compelling reasons to search for physics beyond the Standard Model, particularly for additional higher mass scalar (Higgs-like) bosons.

This dissertation outlines these motivations in Chapter **??**, after a description of the Standard Model. The ATLAS detector and Large Hadron Collider, used to search for the Higgs bosons, are described in Chapter **??**, preceding the description of two searches at different center-of-mass collision energies $\sqrt{s} = 8\,\text{TeV}$ and $13\,\text{TeV}$ in Chapters **??** and **??**, respectively. Both are searches for a high-mass Higgs boson in the decay channel $H \to WW \to \ell\nu qq'$ (qq' referred to hereafter as simply qq). Finally, Chapter 6 discusses the conclusions from both analyses, which offer substantial improvements over the results of previous searches.

Chapter 2

Theoretical Foundations

2.1 The Standard Model of Particle Physics

2.2 The Supersymmerty

2.3 The Non-University Higgs model

Chapter 3

The ATLAS Experiment at LHC

The European Organization for Nuclear Research (CERN[1]) was founded in 1954 and is based in the suburb of Geneva on the Franco–Swiss border. The main function of CERN is to provide particle accelerators and detectors for high-energy physics research. The physicists and engineers at CERN are probing the fundamental structure of the universe using the world's largest and most complex scientific facility — the Large Hadron Collider (LHC) [1]. In the LHC, the particles are boosted to high energies and collide at close to the speed of light. The results of the collisions are recorded by the various detectors. There are seven experiments at the LHC. The biggest of these experiments are ATLAS (A Toroidal LHC ApparatuS) [2] and CMS (Compact Muon Solenoid) [3] which use general-purpose detectors to investigate a broad physics programme ranging from the search for the Higgs boson to extra dimensions and particles that could make up dark matter. The ALICE (A Large Ion Collider Experiment) [4] experiment is designed to study the physics of quark-gluon plasma form and the LHCb (Large Hadron Collider beauty) [5] experiment specializes in investigating of CP violation by studying the b-quark. These four detectors sit underground in huge caverns of the LHC ring. The rest three experiments, TOTEM [6], LHCf [7], and MoEDAL [8], are smaller. The TOTEM (TOTal Elastic and diffractive cross section Measurement) [6] experiment aims at the measurement of total cross section, elastic scattering, and diffractive dissociation. The LHCf (Large Hadron Collider forward) [7] experiment is intended to measure the neutral particle produced by the collider using the forward particles. The prime motivation of the MoEDAL (Monopole and Exotics Detector at the LHC) [8] experiment is to search directly for the magnetic

[1] The name CERN is derived from the acronym for the French Conseil Européen pour la Recherch Nucléaire

monopole.

3.1 The Large Hadron Collide

The LHC [1] is the world's largest and most powerful accelerator which accelerates and collides protons in a 26.7 km circumference crossing the Franco–Swiss border 100 m underground. The LHC is designed for collisions at a centre-of-mass energy $\sqrt{s} = 14$ TeV and an instantaneous luminosity of $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}. The first beam was circulated through the collider on the morning of 10 September 2008 [9]. However, a magnet quench incident occurred on 19 September 2008 and caused extensive damage to over 50 superconducting magnets, their mountings, and the vacuum pipe. Most of 2009 was spent on repairs the damage caused by the magnet quench incident and the operations resumed on 20 November of that year. The first phase of data-taking (Run 1) started at the end of 2009 and the beam energy was increased to a centre-of-mass $\sqrt{s} = 7$ TeV in 2011 and $\sqrt{s} = 8$ TeV in 2012. The total integrated luminosity of 5.46 fb^{-1} was collected in 2011 and of 22.8 fb^{-1} was collected in 2012. Since 13 February 2013 the LHC was in the Long Shutdown 1 (LS1) phase for maintenance and upgrades. On 5 April 2015, the LHC restarted and was operating at a centre-of-mass energy $\sqrt{s} = 13$ TeV throughout the Run 2 phase (2015 to 2017).

3.2 The ATLAS experiment

3.2.1 The Inner Detector

3.2.2 The Calorimeter

3.2.3 The Muon Spectrometer

3.2.4 The Trigger system

3.2.5

Chapter 4

The Electron Isolation Efficiency and Scale Factors

Chapter 5

The Real Lepton Efficiencies

Chapter 6

Conclusion

> *"We must not forget that when radium was discovered no one knew that it would prove useful in hospitals. The work was one of pure science. And this is a proof that scientific work must not be considered from the point of view of the direct usefulness of it. It must be done for itself, for the beauty of science, and then there is always the chance that a scientific discovery may become like the radium a benefit for humanity."*
>
> \- Marie Curie (1867 - 1934)

First, a search for a high-mass Higgs boson in the $H \to WW \to \ell\nu qq$ decay channel was performed using 20.3 fb^{-1} of LHC pp collision data recorded by the ATLAS detector at a center-of-mass energy of $\sqrt{s} = 8\,\text{TeV}$. No significant deviation from the SM background-only prediction is observed. Thus, for both ggF and VBF production modes, upper limits on $\sigma_H \times \text{BR}(H \to WW)$ are set, as a function the Higgs mass m_H, in three different signal width scenarios of a high-mass Higgs boson with a narrow width, an intermediate width, and a SM width. The mass range of the derived limits is $300\,\text{GeV} \leq m_H \leq 1000\,\text{GeV}$, with an extension up to 1500 GeV for the narrow-width scenario.

A second, more model-independent search was performed in the same decay channel using 3.2 fb^{-1} of ATLAS recorded data from the upgraded LHC with pp collisions at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$. The signal widths tested in this search include the previous narrow-width as well as three new intermediate widths at 5, 10, and 15% of m_H. Again, no significant deviations from the background-only hypothesis are observed, leading to upper limits on the $\sigma_H \times \text{BR}(H \to WW)$ for the different signal width scenarios. The mass range of the limits is substantially improved, in regards to the previous search, and extends up to 3000 GeV.

The results from both searches are substantial improvements over the previous results from the ATLAS experiment in terms of both the cross-section times branching ratio values excluded and the mass range explored.

Searches in this decay channel, $WW \rightarrow \ell\nu qq$, are still alive and active! The scalar results presented in Chapter **??** are included in the recently submitted paper [**?**], which combines searches for heavy narrow-width resonances decaying to WW, WZ, and ZZ with final states $\nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$, and $qqqq$. Also, in the course of writing this dissertation, ATLAS has already recorded another 15 fb^{-1} of data at $\sqrt{s} = 13$ TeV! Analysis of the new data is already underway in this channel, adding more data to the previous results and looking into VBF production and the resolved regime.

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